Chapter 9
Pruning

In plantation forestry, pruning involves the removal of live or dead branches for some distance up the tree stem. Its purpose is quite different from that in horticultural crops, where plants are pruned to train them to adopt appropriate shapes and sizes that open their canopy allowing the sun to penetrate and stimulate the production of fruit.

The reasons for pruning in plantations include:

- Producing knot-free wood in the stem, from which high-quality timber can be sawn.
- Maintaining smooth stems, where the plantation is being grown to produce posts or poles.
- Harvesting the leaves for animal fodder, leaf mulch or leaf products such as essential oils.
- Using branch wood as firewood.
- Allowing easier access for animals or for intercropping of trees with other crops in agroforestry.
- Maintaining the health of the plantation, where lack of pruning may attract damaging pests or **diseases**.
- Preventing fallen leaves accumulating in the lower branches of trees, to minimise the chance of fire moving from the ground into the tree crowns.

If pruning is considered worthwhile in a forest plantation, decisions will have to be made about how it is to be done, when in the life of the plantation it should done, how far up the stem each tree should be pruned and how many of them should be pruned. This chapter will consider the issues involved in developing appropriate pruning regimes for plantations.

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9.1 Natural Pruning

Section 2.2 has described how, over the first few years of the life of a plantation, individual tree crowns grow until they meet to form a continuous canopy. The time it takes for this to happen varies greatly, depending on the species being grown, how productive the site is and the stocking density at which the plantation was established. It may be very rapid (1–2 years) on highly productive sites or much longer (10 years or more) on less productive sites. If the stocking density at planting is very low (say less than about 50–100 trees per hectare), the canopies may never touch, because individual tree stems are not sufficiently strong to support the weight of the very wide spread of the branches that would be necessary to cover the gaps between the trees.

Once the canopy has closed, leaves are shed continuously from its base and are replaced progressively by new leaves at its better-lit top (Sect. 2.3.3). Once leaves have been shed from the base, the branches that held them no longer serve any purpose. They too are then shed, eventually leaving the lower part of the stem clear of branches (Fig. 9.1). Branch shedding involves the development of an abscission layer at the base of the branch, a layer of weak tissue. This breaks eventually and allows the branch to be ejected from the stem, usually leaving a small stub. The stem then produces new tissue that grows over this stub, a process known as occlusion. The final result of this self-pruning process is a knot left in the stem wood. The wood that grows beyond the knot is 'clear' (that is, knot-free), although there is usually distortion of the grain for 2–4 cm beyond the knot.

The whole process of branch death, abscission, ejection and occlusion often takes several years. However, different species vary greatly in the time it takes. Some eucalypts need only 1–2 years (Montagu et al. 2003). Other hardwoods take much longer; occlusion after death of branches of silver birch (*Betula pendula*) in Finland took 7–10 years (Mäkinen 2002) and was highly

Fig. 9.1 A branch just about to be shed from the stem of a 3-year-old blackbutt (*Eucalyptus pilularis*) tree, growing in a plantation in northern New South Wales, Australia (Photo—West)

variable for sycamore maple (*Acer pseudoplatanus*) (1–28 years) and common ash (*Fraxinus excelsior*) (1–26 years) in Europe (Hein and Spiecker 2007). Softwood species often shed and occlude branches slowly, some retaining branches for decades (Petruncio et al. 1997; Mäkinen 1999); Taiwania (*Taiwania cryptomerioides*) in Taiwan took at least 9 years to occlude branches after their death (Wang et al. 2003). Hein and Spiecker (2007) developed a model system to predict occlusion characteristics of branches of common ash and sycamore maple.

9.2 Knots and Wood Quality

As discussed in Sect. 3.3.8, knots are the chief source of defect in sawn timber. Australian and South African experience with eucalypts is that knots deriving from branches that had a diameter of 2.5–3 cm or more at their junction with the tree stem are likely to cause appreciable defect in sawn timber (Jacobs 1955; Schönau and Coetzee 1989). Even knots produced from branches smaller than this can cause defects. For example, Marks et al. (1986) studied timber sawn from mountain ash (*Eucalyptus regnans*) trees and found that 85 % of knots deriving from branches of 2–2.5 cm diameter were sufficiently large to produce at least some degree of defect in the timber. However, they also found that the amount of defect declined rapidly as the knot size declined; only 32 % of knots deriving from branches of 0.5 cm diameter produced some defect. Very large knots, deriving from branches with a diameter in excess of 3.5 cm, may cause sufficient defect to weaken seriously the structural strength of eucalypt timber (Neilsen and Gerrand 1999).

The effects of knot size on wood quality are important in species other than eucalypts. Larger knots may be tolerable in some species, probably because the occlusion process is more efficient than it is in eucalypts. MacDonald and Hubert (2002) suggested knots deriving from branches of 5 cm diameter are tolerable in timber cut from the plantations of Sitka spruce (*Picea sitchensis*) in Great Britain. Fahey and Willits (1995) have illustrated the various grades of timber that are sold in the USA and how the presence of knots lowers the grade. Grades vary from the highest-quality ‘appearance’ grades, that are used for timber to be exposed in use for decoration, to ‘structural’ grades, that are used in building construction and must be free of defects that affect their strength, to ‘factory’ grades, that are to be cut up subsequently for use in mouldings or window frames and so on. The highest-quality timber in each grade may be knot-free or may have only a few, small knots. Grade, hence value, declines as both the number and the size of knots in the sawn timber increase.

Given this, if trees are being grown to produce wood of the highest quality for sawn timber production, it is obviously important that their stems should contain a minimum of knots. At least in Australian plantation forestry, this has led to the view that stem pruning should be considered if the trees in the

plantation are going to develop branches larger than about 2.5–3 cm in diameter at their base. Furthermore, the earlier in the life of any tree that branches are pruned from its stem, the higher will be the proportion of completely knot-free wood it will contain when it is harvested finally. Research in Australia (see summary in Montagu et al. 2003) found that in unpruned eucalypt plantations clear-felled at 15–25 years of age, as little as 20 % of the sawn timber obtained from them had a clean, virtually knot-free surface and so was of the highest-quality appearance grade. On the other hand, as much as 60 % of the sawn timber was of appearance grade from plantations that had been pruned early in their life-time.

9.3 Branch Development

As discussed in Sect. 7.2.2, the stocking density of a plantation is probably the most important factor that determines branch size. The results in Fig. 7.5 show that branches with diameters at their base in excess of 2.5–3 cm will be found often on trees in plantations planted at stocking densities of around 1,000 trees per hectare, a planting density used commonly today (Sect. 7.2.4). As discussed in Sect. 9.2, this is a branch size often sufficient to lead to appreciable defects from knots in sawn timber. All the eucalypt plantations included in the experiments shown in Fig. 7.5 were growing on highly productive sites and were only 5 years of age at the time they were measured. This emphasises how early in the life of a plantation branches may reach sizes that can lead to wood defect. In fact, a large proportion of the branches measured in those eucalypt plantations were already dead by 5 years of age, so had reached sizes in excess of 2.5–3 cm diameter even earlier in the life of the plantation.

Not only will the maximum size that branches attain in a plantation increase as the stocking density of the plantation decreases, but so also will the overall **branchiness** of the trees. Branchiness has been defined as the total cross-sectional area, at their bases, of the branches on a stem, expressed as a proportion of the total surface area of the length of the stem along which they occur (Mäkelä 1997; Kellomäki et al. 1989). Thus one tree may be branchier than another because it has either more or larger branches than the other. The branchier a tree, the more work would be necessary to prune it. Both Mäkelä (1997) and Kellomäki et al. (1989) used growth models to illustrate that branchiness of Scots pine (*Pinus sylvestris*) increased as stocking density decreased. Recent developments with this type of model predict not only tree branch development, but also the properties of the wood in the stem and where knots will occur in it (Kellomäki et al. 1999). Other models have been developed to predict branch characteristics of various species around the world (Mäkinen et al. 2003a, b; Mäkinen and Colin 1998; Woollons et al. 2002; Kint et al. 2010). These may be used to assist plantation growers to make decisions about if and how to prune their forests.

9.4 Effects of Pruning

Pruning trees in a plantation may involve the removal of dead limbs only. In species that maintain dead branches for many years (Sect. 9.1), their removal may limit the size of the **knotty core** of the stem, that is, the central part of the stem to which branches were attached before the tree was pruned; the smaller the knotty core of a log finally harvested from the forest, the greater is its value likely to be. Removal of dead limbs may be done also to allow easy access between the rows of the plantation, to remove limbs that catch falling needles and constitute a fire hazard or to provide firewood from the branch material.

As discussed in Sect. 9.3, live branches may reach a size sufficient to cause defects in timber at early stages of development in highly productive plantations (Sect. 9.3). If such plantations are pruned to avoid this, pruning will involve removal of live branches from the lower parts of the stem; of course this will involve the removal also of the leaves on those branches. If plantations are being grown to produce products from the leaves themselves, animal fodder or leaf oils for example, pruning of these plantations will involve removal of live branches also.

Removal of live branches and leaves by pruning has a variety of effects on subsequent tree growth and development (Briggs 1995; Maguire and Petruncio 1995; Pinkard and Beadle 2000; MacDonald and Hubert 2002). The density of stem wood may increase (Sect. 3.3.3), there may be earlier transition from juvenile to mature wood (Sect. 3.3.3), there may be more heartwood produced (Sect. 3.3.5) and stems may become less tapered (Larson 1965; Maguire and Petruncio 1995). All of these responses may be a result of the need for the stem to maintain a constant distribution of stresses along it following removal of the weight of lower branches (Sect. 8.1). They may be a result also of the need to maintain a sufficient width of sapwood along the whole length of the stem to transport water from the roots to the leaves (Sect. 2.1.1). Scientific opinion remains divided as to the exact biological mechanism that leads to these changes in stem characteristics after pruning (Mäkelä 2002); however, none of these changes seems generally to be sufficiently large to have discouraged commercial plantation growers from undertaking pruning.

Perhaps the most important effect of pruning live branches is that it may lead to a reduction in subsequent growth of the tree. The loss of leaves may reduce the total amount of photosynthesis that a tree can undertake, at least for some time following the pruning until the tree can replace the leaves that were removed. However, research results have suggested that as long as no more than about 40–50 % of the leaves are removed from the lower parts of the tree crown of many hardwood species, or about 30–40 % for softwood species, the growth of the tree will be unaffected (Maguire and Petruncio 1995; Pinkard and Beadle 2000; Neilsen and Pinkard 2003; Pinkard et al. 2004; Beadle et al. 2007).

There are several reasons why trees can withstand loss of this much of their leaves without reducing their growth:

- Tree growth rate is determined by the amount of sunlight intercepted by their leaves; this is determined largely by the leaf area index of the plantation (Sect. 2.3.1).

Highly productive plantations, with a leaf area index of 6–8 m^2/m^2, say, usually intercept more than 95 % of the sunlight falling on their canopies. Because many leaves in the canopy normally shade other leaves, the plantation will still intercept about 80 % of the sunlight even when half its leaf area is removed by pruning (Pinkard and Beadle 2000; Montagu et al. 2003; Alcorn et al. 2008b). That is, a large leaf loss does not necessarily mean a correspondingly large reduction in the amount of sunlight that the canopy can intercept.

- Normally, leaves do not function at their maximum photosynthetic capacity. When some of the leaves are removed from a tree, whether by pruning or by other forms of defoliation such as insect browsing (Sects. 10.2, 10.3; Retuerto et al. 2004; Quentin et al. 2011), the remaining leaves are capable of modifying their physiological behaviour and increasing the amount of photosynthesis they undertake to make up for the loss of other leaves. As well, the lifespan of leaves may increase to minimise further leaf loss through normal leaf shedding, until the tree is able to replace the leaves lost by pruning. So large may be these responses, that growth may actually be greater in pruned than in unpruned trees for some time following the pruning (Pinkard et al. 1999, 2004; Pinkard and Beadle 2000; Medhurst et al. 2006).
- The new leaves that develop following pruning are sometimes larger in area than new leaves that develop in an unpruned canopy (Pinkard and Beadle 1998, 2000). This allows them to intercept more of the sunlight falling on the canopy, so allowing relatively more growth to occur in pruned than in unpruned trees.
- As the trees respond to pruning by replacing the leaves that were removed, more of their growth may be assigned to leaf production rather than to stem or root production than is the case for unpruned trees (Reich et al. 1993; Pinkard and Beadle 2000). Thus, trees may respond to pruning by attempting to replace the lost leaves as rapidly as possible, so minimising any loss of growth.

Another important effect of pruning live branches may be the sprouting of epicormic shoots along the pruned stem; these develop eventually into normal leaves or leaf-bearing branches (Sect. 5.5). Redevelopment of branches from epicormic shoots may frustrate completely the purpose for which pruning was done. As an example, Deal et al. (2003) studied epicormic shoot development after pruning and thinning stands of Sitka spruce (*Picea sitchensis*) in Alaska. In this case the trees were growing in native stands, although Sitka spruce is used extensively in plantations in the northern hemisphere. At 6–9 years after pruning, they found profuse epicormic shoot development, with an average of 9–11 shoots developing along each metre of pruned stem. Many of the shoots were of small diameter and may not have led ultimately to large knots in the timber; however, some shoots had developed into branches that exceeded 1.5 cm in diameter at their junction with the stem and so may have been large enough to lead ultimately to some defect in sawn timber. Other work has considered epicormic shoot development after pruning North American conifers (Maguire and Petruncio 1995; O'Hara et al. 2008).

A further important effect of pruning on tree growth and development is that the wound produced by pruning may be a point of entry to the stem for wood

decay fungi (Sects. 11.1, 11.2). There are many such fungi and the decay they cause may render wood quite useless for any commercial purpose. Trees may react to wounding by producing chemicals with antifungal properties and by establishing a barrier zone of tissue within the stem, beyond which decay does not spread further towards the centre of the stem (Eyles et al. 2003) (Fig. 9.3). If this happens, it limits the spread of the decay, but often not before considerable defect has been caused, reducing substantially the quality of the timber obtained ultimately. The season when wounding occurs may affect the extent of decay and sometimes it is more extensive on sites of high fertility (Montagu et al. 2003).

Finally, pruning may lead to a more indirect effect on tree growth and development. If the pruned branches are simply left on the ground, they can provide ideal breeding sites for insects (Sect. 10.2) that damage the live trees subsequently. Johnson et al. (1995) describe a number of examples where this has occurred in northern hemisphere conifers. Others (e.g. O'Hara et al. 1995) have pointed out that the pruned branches may constitute an increased fire hazard if they are not removed from the site after pruning.

9.5 Pruning Regime

If it has been decided to prune a plantation, the decisions necessary to establish an appropriate pruning regime include:

- When and how often during the life of the plantation pruning should be done.
- How far up the stem should branches be removed at any pruning.
- How many and which trees in the plantation should be pruned.

If pruning is to involve removal of dead branches only, these decisions are fairly easy to make. They are rather more difficult when live branches are to be pruned, which is the case commonly in plantation forestry today.

Pinkard and Beadle (2000) have proposed that a general approach to developing a pruning regime for any plantation involves following its leaf area index development over time. As long as it has been determined for a particular species how much leaf removal it can stand without growth loss, knowledge of leaf area index should allow determination at any time in the life of the plantation of the height to which it is reasonable to prune the trees: as mentioned in Sect. 9.4, most species can withstand removal of somewhere in the range 30–50 % of their leaf area index without subsequent growth loss.

It is impossible in a book of this nature to specify the pruning regime appropriate to any particular plantation. The reasons for which pruning is being done, the biological characteristics of the species concerned and the productive capacity of the site on which the plantation is growing will all be important in determining the regime. The following discussion attempts to apply Pinkard and Beadle's principles in devising pruning regimes for plantations.

9.5.1 When to Prune

It is clear from the discussion in Sect. 9.3 that branches large enough to produce knots that cause serious defects in sawn wood can develop early in the life of a plantation. This may be within the first 5 years of growth of highly productive plantations. In less productive plantations, such as the *Pinus patula* and Scots pine plantations referred to in Fig. 7.5, it may take longer for large branches to develop.

Both Pinkard and Beadle (2000) and Montagu et al. (2003) agree that the optimum time to undertake the first pruning is when leaf area index reaches a maximum, at about the time the crowns of the trees have developed sufficiently so that the canopy is just closed (Sect. 2.3.1). Interception of sunlight by the canopy will then be at a maximum, so the amount of light reaching the ground will be minimised. Then, following the arguments of Sect. 9.4, the reduction in sunlight interception will be minimised if part of the canopy is removed at that time.

In rapidly growing eucalypt plantations, the canopy may reach its maximum leaf area index at 3–4 years of age (Beadle et al. 1995; Pinkard and Beadle 2000), or even as early as 2 years of age as in the example in Fig. 2.1. As long as pruning at these young ages does not remove more than about 40–50 % of the lower part of the canopies of trees in these hardwood plantations, there should be no loss of growth and the size of the knotty core of the tree stems should be minimised. In less productive plantations, it may be some years later in their life before they reach their maximum leaf area index and, hence, the age at which pruning might first be appropriate.

If a first pruning is constrained to removing no more than a certain proportion of the leaf area index, the height to which stems are pruned may be less than the total height to which it is desired ultimately to prune (Sect. 9.5.2). This means that pruning will need to be done in several ‘lifts’, that is, on several different occasions to successively greater heights. Each subsequent pruning would need to be delayed until the leaf area index of the canopy has recovered to such an extent that it can stand reduction again without loss of growth; this might be when it has regained about 75–80 % of its long-term, maximum value. Pinkard and Beadle (2000) refer to an example of a highly productive shining gum *(Eucalyptus nitens*) plantation in Tasmania, Australia, where the recovery period was only 13 months after a first pruning lift at 3 years of age. On less productive sites, it may take longer for the canopy to recover sufficiently for subsequent prunings.

If the objectives of pruning are other than the production of high-quality sawn timber, other considerations may determine the timing of pruning. Pinkard (2000) referred to an example where leaf oil and flowers were required from a young age in plantations of Tasmanian blue gum (*Eucalyptus globulus*), plantations that were intended ultimately to produce high-quality wood. She suggested that a very light pruning, before canopy closure at 2 years of age and that removed only about 20 % of tree leaf area index, could be done in these plantations to provide an early yield of oil and flowers. A heavier pruning at that time would lead to a loss of growth of the plantations.

Where the objective of pruning is for other purposes again, such as to provide firewood, access for agroforestry or to prevent the accumulation of fallen leaves, the timing of pruning will often be determined by pragmatic considerations. Thus, pruning might be done when the trees are sufficiently large that animals cannot reach the remaining leaves to browse them or otherwise damage the trees. Or, it might de done when an accumulation of leaves has occurred on dead branches. However, in other cases when pruning of live branches is being done, such as to provide fodder for animals, its timing will also be limited by leaf area development to avoid excessive leaf removal and so reduce tree growth.

9.5.2 Height of Pruning

If pruning is being done to produce high-quality timber, the maximum height to which any tree will be pruned will be no more than the height up the stem from which the larger, high-quality sawlogs will be obtained when the tree is finally harvested. In many plantations today, this will be a height around 6–10 m above ground. Often, this height will be limited by the costs involved. As discussed in Sect. 9.6, the costs of pruning rise rapidly once it is done above a height that workers can reach from the ground. An economic balance, between the cost of pruning and the increased value of the wood resulting from it, will determine to what height it is reasonable to prune and, indeed, if pruning is worthwhile economically at all.

Leaves are not distributed evenly down through the canopy of trees; usually there are more leaves positioned near the middle of the canopy than near its top or bottom. Information in Pinkard and Beadle (2000) suggested that removal of 30–50 % of the leaves at any pruning lift would usually involve removing branches to a height of about 20–45 % of the length of the green crown (that is, from the lowest live branch on the stem to the tip of the tree); other work in various species has confirmed that stem diameter growth is generally affected little until at least 50 % of the green crown length has been removed (Alcorn et al. 2008a; Forrester et al. 2010; Amateis and Burkhart 2011; Springmann et al. 2011; Forrester and Baker 2012). Pinkard and Beadle pointed out that different tree species distribute their leaves in rather different ways along the stem. A study would have to be made of the leaf distribution in the canopy of any particular species before it could be said with certainty how high up the stem it would be reasonable to prune that species at any one pruning lift.

If live branches are being pruned from a species that sheds dead branches fairly readily, it has been suggested there may be little point in wasting time and money by pruning any dead branches that are still persisting on the lower part of the stem. Research with eucalypts has found that the knots produced after natural shedding and occlusion would be little different from those produced if the dead branch had been pruned before it was shed naturally (Montagu et al. 2003). Furthermore, Pinkard (2002) reported that stubs left after pruning dead branches of eucalypts

may break off and be trapped in the occluding tissue leaving kino (a gum exuded by damaged tissues) traces that can further degrade the quality of the wood. However, in species for which the process of branch shedding and occlusion takes much longer than the few years required in many eucalypts, it may be worthwhile pruning dead branches to ensure the size of the knotty core of the stem is minimised. O'Hara et al. (1995) and Maguire and Pentruncio (1995) reviewed experimental results for some North American conifers; in those, the time to occlusion of pruned dead branches was appreciably longer than for pruned live branches and also increased appreciably as the size of the pruned branch increased.

Where the objective of pruning is for purposes other than the production of high-quality timber, pragmatic considerations will often determine the height of pruning. Thus, if animal access is required, pruning would need to be only to a little above the height of the animals. If pruning was being done to minimise the chance of fire ascending into tree crowns through dead leaves caught on dead branches, pruning would need to be to a height somewhat above the flame height of ground fires.

9.5.3 Trees to be Pruned

Usually, it is only at the time of clear-felling of a plantation that trees will have grown to sizes where appreciable quantities of the largest, most valuable logs can be harvested from them. To achieve large tree sizes in a reasonable time, a plantation will usually have been thinned at various times during its lifetime (Chap. 8). Obviously, there is no point in spending money to prune trees that will be removed later at thinning. This means that the final-crop trees will need to be selected for pruning at the time the first pruning lift is done; as discussed in Sect. 9.5.1, this can be within the first few years of the life of highly productive plantations.

The trees selected for pruning will be those that are taller than average, hence are growing most vigorously, and those with the best form, that is, without crooked stems or excessive branchiness. These will be the trees most likely to produce the largest quantities of high-quality timber in the shortest possible time (Sect. 8.3). Neilsen and Gerrand (1999) studied the availability of suitable trees for pruning at 5 years of age in highly productive plantations of shining gum (*Eucalyptus nitens*) in Tasmania. In their case, it was desired to prune 300 trees per hectare that were to be the final-crop trees. They found that unless at least 1,000–1,100 trees per hectare had been planted, there would be insufficient trees of appropriate quality available to choose the desired 300 trees per hectare. That is to say, the availability of suitable trees for pruning may be important when deciding what the original planting density of the plantation should be (cf. Sect. 7.2).

If not all trees in the plantation are to be pruned, it is important that pruning should not reduce the subsequent growth of the pruned trees. Apart from the possibility of economic loss if tree growth is reduced, pruned trees might be overshadowed eventually by faster-growing, unpruned trees. The pruned trees would then

lose their dominant position in the stand and their growth would be reduced even further (Maguire and Petruncio 1995).

When pruning for a purpose other than the production of high-quality timber, the number of trees to be pruned will often be determined by that purpose. If the purpose of pruning is to use the leaves, say for oil production or animal fodder, all the trees in the plantation might be pruned. Similarly, if pruning for access, to provide firewood from the branches or to reduce fire hazard, all trees would usually be pruned.

9.6 Pruning Method

Most commonly, pruning is carried out by hand, with shears or fine-toothed saws. Saws may be mounted on the end of a pole to extend their reach to about 4–5 m above ground. Removing branches with these tools generally leaves a neat branch stub, perhaps of 1–2 cm length. Smoothly cut, neat branch surfaces seem to minimise defect resulting from stub occlusion and the entry of fungal decay (Petruncio et al. 1997; Montagu et al. 2003).

At least amongst American foresters, there seems to be considerable controversy about whether the cut should be made vertically down through the branch, that is, parallel to the axis of the stem, or at an angle away from the vertical, perpendicular to the axis of the branch (O'Hara et al. 1995; Russell 1995). The difference is illustrated diagrammatically in Fig. 9.2. Vertical pruning allows the cut to be made as close as possible to the stem to minimise the size of the branch stub. An angled cut will minimise the size of the wound and so minimise the area available for entry of decay fungi; the level of incidence of decay fungi will probably determine what type of cut is preferred in any particular plantation. In either case, stripping of bark from the stem should be avoided as the cut is made, to minimise the area of entry for decay. Particularly with large branches, this may require that

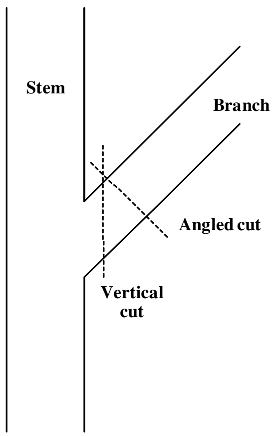

Fig. 9.2 Representation of a vertical pruning cut, made parallel to the axis of the stem, or an angled cut, made perpendicular to the axis of the branchBranch

an undercut be made first, part way through the branch. The cut is then completed from the top of the branch. This avoids the branch snapping off before the cut is completed and stripping bark from the stem as it falls.

Controversy exists also (O'Hara et al. 1995; Russell 1995) about whether the cut should be made through or beyond the swollen ring of tissue where the branch emerges from the stem, known as the branch collar. In hardwoods, the collar often consists only of a swollen ridge within the crotch of the branch (Russell 1995). Cutting beyond the collar minimises the wound size, so minimising the possibility of fungal decay entry (Russell 1995); however, some studies have shown that occlusion occurs more rapidly when the cut is made through the collar (O'Hara et al. 1995), not only because the stub is smaller but also because the tree grows the occluding tissue more rapidly. Montagu et al. (2003) advocated pruning beyond the branch collar in eucalypts to minimise the possibility of decay entry.

O'Hara (2007) reviewed these issues and concluded:

> There is a considerable international body of literature on forest pruning…. The clear majority of this work indicates that a cut close to the stem is effective for pruning forest trees to enhance wood quality without detrimental infections of fungi or bacteria. This body of work indicates that pruning early when branches are small will minimise problems with infections. Other work recommends an outside-the-branch collar method of branch removal and is based on observations of wound response. One consensus that is apparent in this literature is that forest pruning is most likely to be successful in young, fast-growing trees with small branches that occlude quickly and are less likely to be infected by stem decay fungi. This is consistent with objectives in forest pruning of minimising the [knotty] core and reducing costs of pruning…
>
> Foresters and arborists must integrate their knowledge of branch wound response with the suitability of different branch removal methods rather than assuming that a single method is best in all situations.

If pruning is required to heights that cannot be reached from the ground, workers may have to climb trees, perhaps using ladders or spurs on their boots to grip the stem. This is obviously hazardous, slow and expensive. Damage to the stem from spurs may also risk the entry of decay fungi. Whether or not it is worthwhile to climb trees to prune them requires careful economic analysis of the value of the high-quality wood achieved eventually against the cost of the pruning.

Many attempts have been made to develop hand-held, powered devices for pruning. Wilkes and Bren (1986) reviewed a number of them. They include small chainsaws, circular saws and hydraulic or pneumatic shears. They may be powered by small engines carried by the operator or by a larger, centralised power source with hoses running to several devices carried by different operators. These devices are noisy, sometimes hazardous and often unable to make cuts neatly on larger, acutely angled or closely spaced branches.

Attempts have been made also to develop machines to undertake pruning automatically to whatever height is required (Wilkes and Bren 1986; Petruncio and McFadden 1995). These are quite large, self-powered devices that are clamped around the stem base and move up the stem, cutting branches with a chainsaw or knives. As with the hand-held powered devices, they often have problems removing large, acutely angled or closely adjacent branches. Also, these machines may

have difficulty with stems with lumps or bumps and can cause excessive damage to the bark as they move up the stem. These difficulties may offset the advantages of the increased rate at which these machines can prune trees when compared with hand pruning (Petruncio and McFadden 1995). The possibility of using elevating platform vehicles, to carry the operator to height with a hand-held pruning device, has been considered also. Factors such as debris on the ground, steepness of slope or wetness of the site have limited their usefulness. In general, none of the powered devices seems to have gained universal acceptance. Pruning continues to be done most commonly by hand in plantation forestry (Reutebuch and Hartsough 1995; Knowles 1995).

Where decay fungi commonly infect pruning wounds, paints or wound sealants may be applied to each pruned stub to prevent their entry (Montagu et al. 2003). Sometimes, decay entry is more common in warmer weather, so pruning in winter may be recommended (Gadgil and Bawden 1981; Petruncio et al. 1997). For some North American conifers, Russell (1995) suggests that accidental stripping of their stem bark can be minimised by pruning at the end of the dormant season (late winter) or just after new needles form (midsummer).

9.7 Examples of Pruning Regimes

Many different pruning regimes have been developed over the years for different plantations throughout the world. This chapter will conclude with several examples to give some idea of the variety of regimes that are used under different plantation circumstances.

9.7.1 Eucalypts in Australia

Detailed research conducted in Tasmania, Australia (summarised by Pinkard and Beadle 2000), has led to a regime used there for highly productive shining gum (*Eucalyptus nitens*) and Tasmanian blue gum (*Eucalyptus globulus*) plantations being grown to produce high-quality timber (Gerrand et al. 1997; Pinkard and Battaglia 2001; Montagu et al. 2003; Pinkard, personal communication). Plantations are established at about 1,000 trees per hectare and are thinned once or twice during their lifetime to retain 250–300 trees per hectare until clear-felling. At the time of canopy closure at around 3 years of age, the best 350 trees per hectare are selected for pruning; this allows that some of the pruned trees may develop poorly and be removed subsequently at thinning.

The first pruning lift removes live branches for about one-third of the length of the green crown of each tree, leaving them pruned to a height of about 2.5 m; as discussed in Sect. 9.5.2, this degree of pruning should not lead to any reduction in growth rate of the pruned trees. Two further pruning lifts, each removing another

third of the length of the green crown, are carried out when the trees are about 4 and 5 years of age, to heights of about 4.5 and 6.4 m, respectively. The 1-year delay between each lift has been found sufficient for the canopies of pruned trees to reestablish their leaf areas to an extent that allows subsequent pruning without loss of growth.

The entry of wood decay fungi through pruning scars has been found to be a problem in Tasmania (Barry et al. 2005; Deflorio et al. 2007) (Fig. 9.3). In shining gum trees, Barry et al. (2005) found decay columns, averaging 45 cm in length and up to 4.5 cm towards the centre of the stem, spreading in the wood above and below both branches pruned 5 years previously and branches that had been shed naturally. The decay seems to invade at any time of year, so there is no preference in Pinkard and Beadle's regime to prune in any particular season. The timing of the regime ensures that the pruned branches are generally no more than about 2 cm in diameter at their base when pruned; it has been found that the incidence of wood decay increases substantially if branches larger than 2 cm in diameter are pruned.

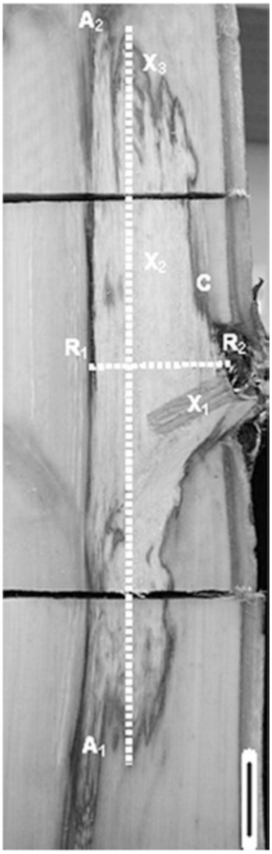

Fig. 9.3 Vertical cross-section through the stem of a 7-year-old pruned Tasmanian blue gum (*Eucalyptus globulus*) tree treated experimentally 13 months previously with the wood decay fungus *Acanthophysium sparsum*. The fungus was introduced by inserting an inoculated wooden dowel into a hole drilled in a pruned branch stub. On the photograph X_1 marks the dowel, X_2 marks a point where decay has occurred and X_3 a point where discolouration has occurred prior to decay. The decay up and down the stem (A_1–A_2) extended 20 cm and the inward decay (R_1–R_2) extended slightly less than 4 cm where a barrier to further decay appears to have been established (Photo reprinted from Deflorio et al. 2007 with permission from Elsevier)

The aim of pruning is to leave branch stubs of no more than 1–2 cm in length and it has been found that pruning shears, rather than saws, are better able to achieve this. Also, shears have been found to cause less damage than saws to the bark surrounding the pruned branch, thus helping to minimise the possibility of decay entry. Care is taken also to avoid damage to the bark immediately above the pruned branch; in these species, this has been found to speed occlusion of the pruned branch stub.

9.7.2 Teak in Costa Rica

Pérez et al. (2003) described a pruning regime for plantations of the tropical hardwood teak (*Tectona grandis*) in Costa Rica. Teak is native to Asia, but it is used extensively in many parts of the tropics to produce high-quality timber.

In Costa Rica, teak plantations are established with about 1,100 trees per hectare and are thinned several times to retain, ultimately, about 120 trees per hectare (Pérez and Kanninen 2005; Table 8.2). Pérez et al. recommended that the trees to be retained after thinning should be pruned in three lifts, first to 2–3 m above ground when the trees are about 4–5 m tall, then to 4–5 m when they are 9–10 m tall and finally to 7 m when the trees are 12 m tall.

On more productive sites in Costa Rica, the trees would be tall enough for the first pruning lift at 2–2.5 years of age. On less productive sites the first pruning would be delayed until about 1 year later. No more than 30–40 % of the leaf biomass would be removed at any of these pruning lifts, the amount that Pérez et al. considered was appropriate to prevent any loss of growth as a result of pruning.

9.7.3 Western White Pine in Northwestern USA

Pruning to both minimise a disease problem and promote the development of clear wood is illustrated in an example for plantations of western white pine (*Pinus monticola*) in the USA (Hunt 1998; Bishaw et al. 2003). This species is native to the western regions of North America and is of interest for plantation forestry there.

In both native forests and plantations, western white pine is affected by the disease white pine blister rust that is caused by the fungus *Cronartium ribicola*. The disease infects needles and causes **cankers** on tree stems and branches, often leading to tree death; the worst infections occur within 2–3 m of the ground (O'Hara et al. 1995). At present, the incidence of the disease is sufficient to limit the use of western white pine for plantation forestry. However, if the lower branches of infected trees are pruned, the development of the disease can be restricted so that its effects on trees are minimal; the reasons for this are discussed in more detail in Sect. 11.3.2.

On the basis of experimental work in Washington, USA, Bishaw et al. (2003) suggested that pruning to minimise disease effects should start either at about 3–5 years of age or when the trees averaged 0.6 to 2 m tall. Pruning should continue in several lifts over succeeding years, perhaps to 5 m above ground to provide ultimately knot-free wood to that level. They suggested pruning should not remove more than one-third of the length of the green crown.

It is clear from the information they provided that their plantations were relatively slow growing by world standards (Sect. 3.2), no doubt reflecting the rather cold climate of the mountain ranges of Washington state. In this regime, pruning at very early ages in these plantations would be principally for disease control; if production of high-quality timber was the only reason for pruning, it would probably be undertaken at a somewhat later stage of development of the plantations.

9.7.4 Spanish Red Cedar in Costa Rica

Cornelius and Watt (2003) discussed the need to prune plantations of the hardwood Spanish red cedar (*Cedrela odorata*) in Costa Rica. This species is attacked by larvae of an insect, the mahogany shoot borer (*Hypsipyla grandella*). The larvae bore into growing tips of trees, retard their growth and cause proliferation of new branches at the tips that can totally destroy the form of the tree for timber production. Members of the insect genus *Hypsipyla* are serious pests of the mahoganies (various species in the plant family *Meliaceae*, including species in the genera *Entandrophragma*, *Khaya* and *Swietenia*) and cedars (species of *Cedrela* and *Toona*) that are important timber species of tropical and subtropical forests in many parts of the world (Newton et al. 1993; Cunningham et al. 2005; Ofori et al. 2007; Opuni-Frimpong et al. 2008a; Sects. 13.2.3, 13.2.4).

Cornelius and Watt found that the form of the trees could be restored after insect attack during the first 2 years of the growth of the plantations. This was done simply by pruning off the multiple shoots, leaving a single main shoot. So severe was the damage caused by this insect that repeated prunings had to be carried out every few months. In this example, pruning was essential to produce any trees with a form acceptable for later use as timber trees. Without it, Spanish red cedar would probably be impractical for use as a plantation species.